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ASTRONAUTICAL SCIENCE AND TECHNOLOGY  
MARCHING TOWARD THE 21st CENTURY

by

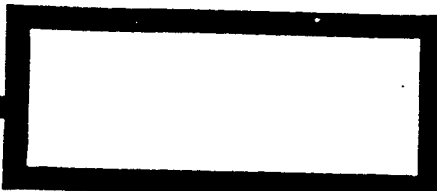
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# ASTRONAUTICAL SCIENCE AND TECHNOLOGY MARCHING TOWARD THE 21st CENTURY

Wang Daoyin

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#### Summary

This book presents the most recent development status and trends of disciplines, specialties and product techniques in the contemporary aeronautical science and technology (AS&T), including general discussions, environment, marketplace, flying vehicles, air-borne equipment and weapon technique, aeronautical materials and manufacture technique, fundamental aeronautical technology, and leading-edge techniques, a total of eight portions. Presentation of status abroad is the main content, striving to reveal whole picture of the world AS&T (with its development regularity) marching toward the 21st century. We believe that this book is helpful to S&T and management personnel engaging in administration, research and production in the aeronautical industry, as well as S&T and management personnel of users utilizing the aeronautical products.

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ASTRONAUTICAL SCIENCE AND TECHNOLOGY  
MARCHING TOWARD 21ST CENTURY

by

Wang Daoyin

FOREWORD

Aeronautical science and technology [AS&T] has become one of the most active and the most influential disciplines in the 20th century for the understanding of man and transformation of natural processes. Since the short flight of the first powered and maneuverable airplane by the Wright brothers early in this century, man's age-old dream of flying in the atmosphere has eventually become a reality. Following decades of exploration and struggle by several generations of outstanding personalities, aeronautics as a science and technology has rapidly progressed with continuous upgrading of aircraft performances. Aeronautical weapons and equipment have become the most important tool for the defeat of the enemy in the modern warfare; aircraft have become an indispensable means of transportation for the national economy and people's livelihood; a prosperous aeronautical industry is a vital mark of scientific progress and industrial development of the world nations.

Aeronautics as a science and technology is a highly integrated modern endeavor based on fundamental science and

technical science, applying the most recent achievements of many disciplines in this century. The aeronautical industry is a high-tech undertaking with high integration of multiple fundamental industries, known as the "flower of industry." As the leading edge of high-tech discipline, aeronautics continuously feeds fresh blood to other industries in the national economy with its numerous achievements in science and technology. Therefore, the world's developed countries and some new developed countries compete in developing AS&T. The aeronautical industry has become a key strategic industry of the world nations. After decades of development, aeronautics has become a relatively complete system at the leading edge of development in realms of mechanics, thermodynamics, materials science, computer science, jet propulsion, automatic control, microelectronics, and manufacture technology. After entering the eighties, with more extensive applications of computers, microelectronics, new materials and new technologies in AS&T, and emergence of new powered systems, new electromechanical systems, new weapon systems as well as new aerodynamical layout and new mechanism structure of modern aircraft, flight vehicles are developed leading to further integration, as well as being information and intelligence oriented. New breakthroughs have been attained in aircraft mobility, adaptability and economy. A large number of high-tech processes have been gradually and extensively applied in research and development of the stealth technology, supersonic cruising, trans-stall technique, integrated control techniques of flight control, firepower control and thrust control, integrated techniques for aircraft propulsion, over-the-horizon attack techniques, air-to-ground precise guidance and multi-target attack, highly integrated avionics systems, forward looking infrared night vision, combination of GPS and inertia guidance, air-borne powered phase control array, advanced composite material structure, computer integrated manufacture and simulation, as well as aircraft reliability and maintenance engineering. New and rapid progress

is impending for the AS&T.

The final five years of the 20th century are drawing near. These five years are the Ninth Five Year Plan period of China on development of the national economy. On the occasion of welcoming the new century, the pace of AS&T does not slow down around the globe even during conclusion of the Cold War, bringing with it a shrinking of the scale of the aeronautical industry. Conversely, many nations still emphasize the technical reserve of AS&T, striving to maintain technical superiority. For readers to understand the most recent developments and trends of disciplines, specialties, product techniques of the AS&T on an overall scale, we have organized scores of specialists, who have pursued, analyzed and studied aeronautical information for a long time at the China Aeronautical Information Center to compile this book with the purpose of reviewing all realms of AS&T. The contents of the book mainly presents information from abroad, attempting to show from many sides the status of AS&T marching toward the 21st century. Development trends are discussed.

A unified format is adopted in writing and compiling the book. Every chapter includes the following portions: Foreword, Development Status Abroad, and Development Problems Appearing With Regularity. In the Foreword, descriptions are given of the study scope and definition, as well as the aim of the chapter. In Development Status Abroad, an overall description is given of techniques within the scope of this study, revealing the situation in the most recent developments abroad. The demand-driven principle is followed in the description, emphasizing key points. Descriptions of Development Problems Appearing With Regularity include the technique itself, and the related ones of industry, economy, management of the environment, as well as the relationship between the techniques and the major AS&T. The contents of this portion are the key points of every chapter.

In compilation and writing of the book, technical advisors were employed; those advisors are veteran leadership and expert personnel in various technical realms of AS&T with broad knowledge and abundant experience. They were very helpful in revising the draft; we express our sincere gratitude to them.

Flying into the blue yonder (faster, higher and more remote) has always been man's desire, which has been fulfilled in the 20th century. Today, with the light of the 21st century coming over the horizon, we expect that the development of AS&T will benefit mankind by promoting scientific and social progress, achieving more glorious success over the 20th century. May this book make its feeble contribution to the development of AS&T and a leap forward of aeronautical industry in China.

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EGI: Inserted into GPS receiver  
Glonass: Global navigation satellite system  
GPS: Global positioning system

#### 2.1.2.5 Avionics equipment

One of the fastest moving technical developments in modern jet transport planes is avionics equipment. New avionics equipment devices are applied in aircraft maneuvering (telemaneuvering systems), full-weighted digital control of the engine, communication guidance (global positioning system) and cockpit display (electronic flight instrumentation system). The electromechanical instrumentation of the old days for cockpit

displays was replaced by cathode-ray tube electronics display; therefore, the cockpit has become known as the glass cockpit. Applications of the modern avionics equipment have greatly relieved the work load of the pilot; thus, the five-member aviation team previously consisting of a pilot, a copilot, a navigator, a radio operator, and an engineer has been reduced to a dual-member team of a pilot and copilot. Thus, the direct operating expenses of aircraft have been considerably reduced but with greater safety. Although the number and types of airborne electronics equipment have been considerably increased the aircraft weight is not increased. In the past two decades, the weight of avionics equipment has been consistently maintained to about 1 percent of the aircraft weight [9]. The reason that avionics equipment can be maintained at such low weight is because of applications of solid-state circuitry and microprocessor with digitalization, integration and miniaturization.

In developing the Boeing 777 airliner, the avionics equipment is further integrated; a system of aircraft information management includes flight management, flight navigation display generator, maintenance, communication management, engine data interface and data converting channel with sharing of resources, with 20 percent weight reduction, 30 percent less power consumption, higher reliability, 50 percent longer in mean malfunction interval, and 100 percent longer time in mean interval for nonperiodic dismantling of parts.

Integration of airborne electronics equipment is related to development of a data trunk line; its application allows sharing of information by sensors, detectors, processors and displays, thus avoiding duplication of hardwares. On the Boeing 777, the ARINC 629 data trunk line has been developed, which is as simple as two twisted wires connecting all replaceable parts. Thus, previously an airliner required 400 bundles of wires, with 33,400

segments and 4860 connectors, 114 km long and weighing 1179 kg; now, an airliner only requires wires in 400 bundles, 9322 segments and 1580 connectors, 48 km long and weighing 658 kg.

As an example of miniaturization of avionics equipment, a liquid crystal plate display has been used in developing the Boeing 777 to replace the previous cathode-ray tube. Although the dimensions of the display board are still 200 mm x 200 mm, its thickness is reduced to 152 or 254 mm. It is easy to install such thin boards on the front instrument panel. As announced by the Boeing Corporation, volume, weight, cost and power consumption can be reduced, respectively, by 60, 70, 70 and 80 percent, as compared to the plate display board with the cathode-ray tube display, while reliability is greatly upgraded.

With development of AS&T, many new equipment pieces have been added in the modern subsonic transport planes with the following as the relatively important devices.

Global positioning system (GPS): its complete name should be guided navigation satellite timing and ranging global positioning system. This is a three-dimensional guided navigation system based on a geostationary satellite system. A GPS system requires to place 21 operating satellites and 3 reserve satellites in space. At present, all satellites have been placed into orbit in early March 1994, providing positioning data 24 hours around the clock.

The global satellite navigation system is a navigation system with the highest precision and the most remote operating distance. The navigation precision may be as high as 5 to 30 meters for civil transport plane installations with receivers.

The satellite navigation system not only can be used in navigation but also can serve as precision landing equipment for

the airfield approach (pilot's decision-making altitude is 60 meters). Its price ratio is lower than other landing systems (U.S. \$100,000 for three-kind instrumentation landing system, \$80,000 for microwave landing system, and \$45,000 for GPS system). Although the International Civil Aviation Organization has decided to replace the present instrumentation landing systems with microwave landing systems before 1 January 2000, there is a dispute underway as to whether it is better to use GPS systems instead of the microwave landing systems to replace the instrumentation landing systems.

Wind shear detection, alarming and collision avoiding system: wind shear is due to sudden change of wind speed or wind direction in nature. Wind shear which causes significant deviation of the course of aircraft at landing or takeoff can result in collision with the ground. Wind shear may be caused by thunderstorms, cold fronts, warm fronts, or ocean wind fronts in addition to the more dangerous micro-storm, which is an intensive descending current in a small area. When an approaching aircraft enters into a micro-storm, first it is faced with head-on wind to increase its lift, thus deviating the aircraft upward. So the pilot instinctively reduces the engine power. However, the aircraft is confronted in the next instant a strong tail wind to reduce the lift, thus deviating from the downward gliding path with drop of height possibly over 100 meters, causing the aircraft impact with the ground resulting in destruction. The wind shear devices installed on aircraft before 1989 can only sound an alarm to the pilot when wind shear is present. The later wind shear detection, an alarming and guiding system developed by the Honeywell Corporation for MD-80 planes, can let the pilot decide whether to operate an automatic piloting instrument to control the execution of an evading action maneuver.

Air traffic alarming and anti-collision system (TCAS) is an

anti-collision system in air. The International Civil Aviation Organization calls it an airborne anti-collision system. There have been quite a few collisions between aircraft in the air. By increasing the number of planes flying along air routes, the possibility of collision becomes greater. It is inadequate to rely only on the ground control system of air traffic and visual judgment of the pilot as to whether or not another approaching aircraft is flying head-on. Therefore, such airborne alarming and anti-collision system must be installed on the plane. TCASI is an alarming device developed for general aviation planes and airliners of 10 to 30 seats operating along branch air routes. TCASII is an equipment for large commercial planes, not only having functions of the TCASI, but also the capability of telling the pilot how to take evasive actions. If both planes flying in opposite directions have TCASII installed, they can talk to each other in coordinating the evasive action in addition to making proposals to the respective pilots.

The near ground pilot warning system (GPWS) can release a warning call, "Pull Up, Pull Up" as safety warrants. Based on statistics, one of major causes of major airplane incidents in the world is negligence or absentmindedness of the pilot flying the plane, resulting in impact with the ground or a plunge into water. These incidents have a special term: ground impact of controlled plane during flight. In the mid-seventies and early eighties, the U.S. and International Civil Aviation Organization required large transport planes to install such near-ground warning systems, thus greatly reducing such incidents.

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## 2.2 New High Technology in Aeronautical Weapon Systems Abroad

Aeronautical weapon systems are among the contemporary high-tech weapons. Facing future high tech wars, various high-tech



methods will be extensively applied in the aircraft weapon systems. There are mainly the seven following high-tech approaches.

#### 2.2.1 New concepts in technology of aircraft guns

The new concepts for aircraft guns consist of a series of aircraft firing weapons with brand new mechanisms which represent a breakthrough from old concepts of the traditional aircraft guns. These new concept guns are liquid guns, gas guns, electromechanical guns, laser guns, plasma guns, and particle beam guns (referring to the chapter, High Energy Tactical Weapons, in this book). The traditional aircraft guns applied solid firing powder for power to propel the bullet along the gun barrel, thus acquiring the muzzle velocity and direction required to fly toward the target. However, the muzzle velocity is just the unbreakable barrier of the traditional aircraft guns. In theoretical calculation, the limit of muzzle velocity is 2969 m/s.

In studies of specific energy and combustion rules for various materials used for the energy source, it has been discovered that liquid firing material is greater in specific energy, and lower in explosion temperature than solid firing powder, thus with higher muzzle velocity and firing speed, as well as lessening erosive wear of gun barrel. Thus the aircraft

gun using liquid firing material has appeared on the scene. Its working substance is still gasified gunpowder; in this case, although the muzzle speed of the bullet is as high as 2090 m/s, approaching the muzzle speed barrier of the traditional aircraft guns, yet the limit is still not surpassed. So a new working substance should be found; the gas fired gun appeared with muzzle speed as high as 11,000 m/s in the case of guns with hydrogen as working substance. However, erosion of the gun barrel still exists. Then, various new concepts for guns subsequently appeared, such as an electromagnetic gun using electromagnetic force as energy source, and beam energy (directional energy) guns, such as laser guns, particle beam guns, microwave guns, and plasma guns, among others.

Key areas of the new concepts for aircraft guns are as follows.

- General techniques: studies of the functions and mechanisms of new-concept aircraft guns, as well as studies of miniaturization, and studies on installation feasibility;

- Materials with high energy sources: liquid and gas working substances with higher specific energy;

- Electromagnetic firing: peak pulse energy source and accelerators (guided rail, coil and direct magnetic field); and

- Beam energy firing: laser beam energy, particle beam energy, microwave beam energy, and plasma beam energy.

### 2.2.2 Air-to-air missiles of the newer generation for close combat

Development of air-to-air missiles for close combat has passed three generations; currently, this is the fourth generation. Since a series of techniques (such as anti-jamming; infrared imaging guided head; low gas dynamic force surface with low drag exterior, high thrust low (or no) smoke solid-fueled rocket engine thrust vector control) are adopted, the missiles have been significantly upgraded in firing range, speed, precision, off-boresight firing and omnidirectional attacking capability.

There are the following key techniques for the newer generation air-to-air missiles for close combat.

- Multi-element infrared focal plane array gaze imaging;
- Thrust vector control;
- Single chamber dual thrust low or no-smoke solid-fueled rocket engine;
- Anti-infrared jamming;
- Directional firing warhead; and
- Large off-boresight angle/shoulder firing.

### 2.2.3 Air-to-air missiles for over-the-horizon targets, fire-and-forget

Such missiles have been developed from the close distance air-to-air missile (appeared in early fifties) with wave beam guidance and tail attack. In the late eighties, new models of intermediate and close distance air-to-air missiles appeared, having the functions of pulse doppler system active radar terminal guidance and intermediate segment command combined guidance, as well as over-the-horizon target with fire-and-forget feature, and multi-target attack capability.

The key techniques of air-to-air missiles for over-the-horizon targets with fire-and-forget feature are as follows.

- Advanced stealth with gas-dynamic exterior;
- Advanced combined guidance and dual-mode guidance;
- Composite type rocket/jet engine and multi-stage propulsion;
- Intelligent type firing and high power warhead technique;
- and
- Intelligent type anti-jamming.

#### 2.2.4 Standoff air-to-ground weapons firing outside of the defending area with precise guidance

Such weapons include air-to-ground missiles and guided bombs released outside of the defending area. These missiles include strategic air-launched cruise missiles, and general tactical air-to-ground missiles fired outside of defending area; these bombs include various types of guided bombs.

The key techniques of precise guidance of the air-to-ground weapons fired outside of the defending area are presented as follows:

- General scheme of the airborne weapon systems and system technologies: interface techniques and mathematical model determination for weapons and airborne sub-systems, analysis of parameter precision of sub-system interface for weapons and airborne equipment, interface techniques and anti-jamming of data link transmission systems for the weapons and airborne equipment.
- Design of the aerodynamic exterior of missiles: optimized design of dynamic exterior, monowing exterior layout for pitching and turning (BTT) control, wide-body folded type monowing exterior layout with high lift-to-drag ratio, stealth aerodynamic exterior layout, and modular structure layout.
- Guidance techniques: quick connection inertia guidance/global positioning system (SINS/GPS) combined guidance,

millimeter wavelength radar, laser, television and infrared imaging guidance, intermediate segment guidance and data link transmission, and terrain matching/scene matching guidance.

-- Engine technology: miniature highly efficient turbofan/turbojet engine, hybrid rocket/ram jet engine, and tunnel type rocket engine.

-- Warhead/detonation method: single highly effective warhead (armor rupture, dynamic energy armor piercing, forming with forging, directed explosion, and others), dispenser type multi-function warhead (including various types of guidance/non-guidance bomblets and sensor triggered bomblets), and intelligent warhead fuse.

#### 2.2.5 Firing control system for over-the-horizon multi-target attack

This weapon system for attack of multiple targets over the horizon began to be developed in the late fifties by the U.S. The development was successfully concluded in the early seventies, capable of simultaneously tracking 24 targets and attacking 6 targets. Such weapon system is composed of model AWG-9 over-the-horizon multiple targets attack firing control system and model AIM-54A Phoenix close-distance air-to-air missile; the weapon system was carried by the F-14A shipborne long-range interceptor. Later, fire control systems for over-the-horizon multiple targets attack have also been equipped on new fighter planes of the U.S., United Kingdom, France, and former USSR/Russia, among other nations.

The key characteristics for an over-the-horizon multiple targets attack fire control system are as follows.

- General scheme, system precision and stability of firing control system;
- Highly effective pulse doppler firing control radar;
- High performance infrared search and tracking equipment;

- Multiple targets friend-or-foe and modular discrimination;
- Multiple targets tracking, filtration and display;
- Multiple targets attack decision making, threat decision making and firepower distribution;
- Multi-sensor integration, data fusion and tactical information processing; and
- Equipment carrying plane evading technique and dynamic compensation technique.

#### 2.2.6 Streamlined exterior suspension mounted/high density interior suspension mounted techniques

The streamlined suspension method was proposed for further upgrading the flight performance and maneuverability when hanging a large number of weapons on a supersonic combat plane. The more ideal weapon suspension method is to hang objects tangent to the exterior surface, or suspend them semi-embedded. The high density interior suspension method was proposed for the recent stealth combat planes. To effectively utilize space inside the weapon compartment, and to increase the carrying capacity of ordnance, the deployed air-to-air missiles suitable for exterior suspension are to be revised and the high density interior suspension technique is to be developed.

Key techniques of the streamlined exterior suspension/high density interior suspension are as follows.

- Tangent to fuselage/semi-embedded exterior suspension, and high density suspension in the weapon compartment;
- In-compartment rotary/extruded type suspension;
- Mode firing/ejection multi-function suspension;
- Highly effective pollution-free ejector energy source;
- Weapon with tangent tip/folded missile wing aerodynamic exterior layout;
- Weapon with oval shaped missile (wingless) aerodynamic

layout controlled at tail; and

- Safety separation between the weapon and its carrying plane.

#### 2.2.7 Advanced management system for the suspended object

The forerunner of the suspended object management system (SMS) is the electromechanical firing control box and electromotive bomb release apparatus with independent operation in early times. In the early seventies, there appeared the primitive stage suspended object management system with microcomputer connected to special divergent wires. Later, new suspended object management systems appeared on the scene with heavy structure, dual channels, and multi-microcomputer; such system has been widely applied in such advanced fighter planes of F-15, F-16, F/A-18, Hurricane and Phantom 2000 types.

Now the configuration of SMS has been changed from analog to combined digital-analog type. Development is underway toward the completely digital type.

Key techniques of the advanced SMS are as follows:

- Hard point interface, aircraft interface, man-machine interface, and standardization of the three;
- Suspended object management processor, as well as computer language and software;
- Avionics multi-channel data trunk line and ordnance trunk line; and
- Suspended object management display and control.

## ADVANCED AVIATION NAVIGATION TECHNOLOGY

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### ABSTRACT

Mainly, there are radio and inertia navigation systems for modern flight vehicles. With practical applications of satellite navigation, such as GPS as a typical example, the combination applications of inertia/GPS technology have been gradually expanded. This article stresses the general development status of the above-mentioned systems abroad. Five problems appearing with regularity are summarized so that readers may have an overall understanding of contemporary flight vehicle navigation technology from the viewpoint of technical development.

Key words: Inertia navigation, satellite navigation, global positioning system, combined navigation and gyroscope.

### 1. Foreword

What is termed navigation is guided navigation. It means the procedure of an aircraft flying from a point to another point along a predetermined air route. The so-called guidance is the controlled guidance, indicating the behavior procedure of a flight vehicle arriving at a predetermined destination following a definite locus or command. In the past, navigation consisted of two different procedures. Since the precision and cost-to-effectiveness ratio of advanced navigation can satisfy the requirements of aerial weapon guidance, this procedure has become an important component in the modern combined, controlled navigation; its application has been continuously expanding.

There are quite a few means used for accomplishing navigation tasks. Based on whether or not ground equipment or external information is available, the navigation system can be



divided into two major types of dependent and independent navigation. Based on different technical means of obtaining navigation messages, the navigation systems can be divided into radio, satellite, inertia, astronomy, terrain reference, doppler and instrumentation navigation, among others.

Among the many navigational means, mainly radio navigation and inertia navigation are used by modern aircraft. With practical application of satellite navigation (such as GPS), radio navigation will be gradually replaced while inertia and GPS in combination will be extensively applied. At the same time, the inertia system will also be further upgraded toward a higher performance-to-price ratio.

The central theme of this chapter is the study of the airborne inertia navigation system (INS), the global positioning system (GPS), the combination of INS/GPS and other combinations. We have to emphasize that the combinational navigation will be the main trend of development from the present time to early 21st century.

## 2. Development Status Abroad

### 2.1 Renewal of navigation equipment is stressed in remodeling old aircraft.

Beginning in 1994, the United States spent approximately nine billion U.S. dollars annually for research and development (R&D) as well as purchases of military avionics equipment. New research items will be limited but opportunities will grow with remodeling of old aircraft. Renewal of avionics equipment is an important part of remodeling old aircraft, but the navigation system makes up the main portion of the avionics equipment [11].

Replacement of old electromechanical gyroscope systems by

new inertial guidance systems (such as the laser gyroscope standard inertia instrument) began in the mid-eighties. Beginning in the late eighties, GPS has become the largest project for improvement of avionics equipment in the history of U.S. Air Force [27]. In 19 years from 1988 to 2006, it is predicted that nearly 12,000 military planes will be equipped or remodeled with GPS receivers that are mainly used for navigation, with a total investment of nearly 1.8 billion U.S. dollars. This remodeling task of military planes is also developed in the air forces of NATO countries. Among relatively important projects including remodeling of avionics equipment with renewal of the navigation systems, there are the following projects: multi-nation improvement project in different stages on F-16s; renewal project of avionics equipment of C-130H planes; navigation/firing control improvement project of B-52 bombers; the F-111 First Row Soldier attack project of the U.S.; Hurricane standard model intermediate-stage renewal project and Panther navigation upgrading project of the United Kingdom; the upgrading project on navigation of the French export model Mirage III; and avionics equipment upgrading project of C-130 planes of Canada, among others. Among these projects, digital terrain matching systems and microwave landing systems have been adopted on F-16 planes. Due to expenditure limitations, terrain reference navigation systems have been given up in upgrading of Hurricane planes.

In civil aviation, from a conservative estimate by the U.S. Federal Aviation Agency (FAA), 4000 commercial and general aviation planes will be equipped with global satellite navigation systems (GPS or other satellite positioning systems) in the mid-nineties, 80,000 planes in the year 2000, and 200,000 in 2010. Equipped on planes, the GPS receivers will be able to accomplish tasks in all flight stages, including midway navigation, transoceanic flight and precision approach/landing [27].

## 2.2 Speeding up innovation on aviation aircraft navigation by GPS

### 2.2.1 Aviation applications of GPS are speeding up.

The U.S. Clinton Administration announced a proposal titled "Promotion of the Aeronautical Industry With Intensive Competition" in January this year. The proposal urges the introduction of GPS in the procedures of aircraft navigation, approach and landing. As a clear target, within the year 1994 GPS air route navigation and landing should be implemented. GPS should be applied in transoceanic navigation with the year 1995. Implementation of an upgraded GPS system should be adopted in 1996 for precision landing and approach. The pace is at least two years ahead of the previous schedule.

The background of Clinton's administration advancing this proposal is the following. The entire GPS satellite complex, including 24 satellites (21 operating and 3 reserve satellites) were deployed in November 1993. Hereafter, the GPS satellite complex will provide initial operating services for commercial and civilian users around the globe. This means that users can be guaranteed to rely on signal grades of the standard positioning service (SPS) in obtaining a horizontal positioning precision of 100 meters at least 95 percent of the time. The U.S. Department of Defense (DOD) has the responsibility to inform the FAA and Coast Guard 48 hours before interruption of satellite operation in any program.

### 2.2.2 The U.S. military does not give up its control on GPS.

Although the commercialization pace of GPS is alarmingly fast, and the U.S. government has decided to let its Departments of Defense and Transportation jointly manage the GPS network, yet DOD never admits to giving up its management and control of GPS. The Pentagon not only rejected the request by the commercial circles to eliminate the selective accessibility (SA), but

further reinforced its control on GPS encoding and anti-jamming capability. On 31 January this year, the Pentagon advanced its permanent implementation of anti-deceiving (AS). AS is an encoded telegram message with P code enciphering [16]. In addition, control has been intensified on antenna techniques of GPS receivers, such as military supervision of production of the controllable receiving direction pattern antenna (CRPA), which is capable of counter-jamming. Besides, the Pentagon is closely watching the development of wide-territory difference modification, and seeking a feasible way to restrict the wartime services of differential GPS (DGPS). In dealing with the problem that GPS signals may be jammed in wartime, the U.S. military is developing a specialized technique: when enemy jammers broadcast jamming signals one billion times the GPS signal intensity, GPS receivers can still detect the navigation signals [6]. This summer, the U.S. Joint Electronics Warfare Center (JEWEC) proposed several research programs on electronic countermeasures or anti-jamming techniques for military GPS receivers. Other than those mentioned above, by adopting a specialized antenna array to provide electronic countermeasure techniques for GPS receivers, these projects include a program on tactics or operation to detect manual or other jamming, and for discrimination and positioning. Besides, JEWEC is developing a prototype of a jammer in order to jam the enemy's GPS systems [23].

#### 2.2.3 The International Civil Aviation Organization Expedites the Execution of the FANS program.

The Future Air Navigation System (FANS) was proposed by the International Civil Aviation Organization (ICAO) in 1988. This is a system program with satellites as the basis and including communication/navigation/surveillance (CNS). As estimated by the ICAO, by raising the efficiency of air route determination and upgrading aircraft efficiency, the FANS system will bring about annual benefits of 5.2 to 6.6 billion U.S. dollars. In the ICAO project, the FANS program will be in the feasible stage in the

year 2000. At that time, all aviation users should be converted to the new system; however, an overlapping time of five years is allowed. In 2006, all the present radio navigation systems will be dismantled. As the first step, announced by the Pentagon recently, in December 1994 demands on Omega/very low frequency remote distance radio navigation systems will first be terminated.

The FAA has actively recommended to the ICAO that this project is to be undertaken by GPS. Recently, ICAO is negotiating with the United States and Russia on the problem of guaranteeing to use their satellites (GPS and Glonass) as the basic navigation systems [12]. Since the European nations are consistently worrying about GPS control by the U.S. military, the European Union has agreed to adopt GPS and Glonass as the transitional stage toward the implementation, in the near term, of an independent future global commercial satellite navigation system.

### 2.3 Start of equipping the combined navigation system

In recent years, applications of the combined navigation system were expanding. The system has been esteemed by aviation circles. With respect to civil airliners, light and small model planes mainly use the combined system of Roland/territorial navigation/GPS. However, large long-range civil airliners mainly adopt the program of inertia navigation/inertia datum/Omega-very low frequency (or any combination of these systems). For military planes, a combination of GPS and the inertia system occupies a very important position. This can be proved by the three following military programs.

#### 2.3.1 EGI program [5]

In early 1993, the Pentagon designated the U.S. Air Force to

lead the development of a program titled Inertia Guidance System with Inserted GPS Receivers, briefly called EGI. The main purpose to develop EGI is to protect the P code signal in enciphering the GPS. In the military plan, a total of 3600 sets of EGI systems will be produced within five years after 1994. First batch of such system will be operated on F-15A/B/C/D planes of the U.S. Air Force, the AH-1W helicopters of the U.S. Marine Corps, AH-64 helicopters of U.S. Army, OH-58D and a series of helicopters for Special Forces, F/A-18 planes of U.S. Navy, and C-1301 transport planes.

#### 2.3.2 GINA program [5]

The U.S. Navy has picked the GPS inertia navigation module (GINA) with inserted GPS receivers to equip its T-45 trainer planes. This is one segment of the Navy's Cockpit Upgrading Program, aiming at using the GPS/INS combination system to replace the previous standard attitude navigation direction reference system (SAHRS). At present, test flights are being conducted on the GINA system. In a production plan, 390 sets of GINA system are going to equip on the T-45 planes. The potential application includes shipborne planes and air force planes to be sold overseas.

#### 2.3.3 The GGP program [5]

The U.S. Advanced Research Planning Administration (ARPA) is supporting a program titled GPS Guidance Module Project (GGP), planning to make a series of equipment with combination of solid state inertia sensors and GPS small receivers to be installed in various models of tactical guided missiles. First batch of two sets will be delivered in September 1994. It is expected that the system precision will be better than 10 meters (SEP-standard probable error).

Besides, with maturing of digital map techniques and large capacity mobile random memory chips, and successful development of a newer generation holographic lens star tracker, the inertia/terrain matching and inertia/astronomical combination system has been successfully applied in some planes in executing strategic missions. For example, B-1B and B-2 adopt star trackers combined with the INS/GPS system. F-16, Hurricane and Gale planes apply the terrain matching reference navigation technique.

#### 2.4 Inertia combination guidance upgrades precision of aeronautical ordnance

With new accomplishments in the small size/low cost inertia equipment and modern digital circuitry techniques, GPS can be further integrated into new applications of smart bombs, terminal guidance of artillery shells, and drones, thus converting heavy weapons into intelligent ones. In the following, current major topics are described in the field of precision guidance bombs, thus indicating infiltration and expansion of inertia guidance technology into new fields.

##### 2.4.1 JDAM program [10]

This is a program of the three Armed Forces, led by the U.S. Air Force. The program deals with the main task by integrating a GPS receiver/inertia guidance module into the tail cone of a JDAM, joint direct attack weapon module, thus converting the non-guidance bomb into an all-weather precision attack weapon. The precision of such bomb is 3 meters, in probable circular error. Design evaluation of the JDAM was concluded in March 1993. The final development lasting 36 months will be conducted as follow up. Within the next 15 years, demand on JDAM will exceed 74,000 sets. It is estimated that the equipping cost for each set will be less than 40,000 U.S. dollars. The JDAM will be carried by F-22, B-1 and B-2 planes.

#### 2.4.2 JSOW program [illegible]

The JSOW, joint operating weapon outside of defense perimeter, also enters its development stage. Like JDAM, JSOW also applies the GPS/INS combination system for guidance. JSOW will be carried by the B-1 bomber.

#### 2.4.3 TMD program

TMD is an upgrading program of the tactical bomb dispenser. With installation of GPS/inertia guidance, the weapon will allow a combat plane to drop TMD at a high altitude without lowering its precision. In an evaluation report of advanced ordnance in 1992 by the U.S. Air Force, demand for an upgraded TMD is stressed. However, the formal start of the development may begin in 1995. It is estimated that the total number of TMD used in the battlefield is between 25,000 to 60,000.

#### 2.4.4 Remodeling program of AGM-130

The AGM-130 guided missile fired outside of the defense perimeter is carried by F-111 fighter planes. The missile has manually guidance circuitry. After installing the intermediate segment inertia/GPS guidance, the upgraded AGM-130 will replace the present manual guidance; trajectory revision can be made in midcourse before reaching the target. It has been determined that 298 AGM-130 missiles are to be required to install the inertia/GPS package.

#### 2.4.5 VAIN program [13]

One of the important steps forward in applications is surveying and compensation of the vibration and deformation of a moving object. With more urgent demands on precision aiming by



using intelligent fuselage materials, the U.S. Air Force is designing a kind of advanced inertia network of vital components (VAIN) for military aircraft. VAIN can compensate, at all times, the bending deformation and vibration of some components (such as aircraft center of gravity, front fuselage, weapon compartment and hanging frame), thus ensuring precision of target attack by combat planes in all weathers. Those planes preparing to apply this technique are possibly the F-16, F-15 and F-22. Network is a concept of regional supplements with integration of multiple inertia sensors, deflection sensors (possibly empty fiberoptics sensors) and GPS. Contract documents on VAIN are expected to announce in March 1995. The total budget of development expenditure is 2.8 million U.S. dollars.

2.5 Solid state inertia sensors are of major importance in the aircraft inertia guidance market

The gyroscope and accelerator are the key input sensors in the inertia systems. Among quite a few precise gyroscopes used in aircraft inertia guidance systems, these electromechanical gyroscopes (such as electrostatic gyroscope, air shaft liquid floating gyroscope and dynamic tuned gyroscope) have attained an advanced upgrading stage. Their performances have been steady. Further improvements are not only relatively difficult but also not necessary. At present, these gyroscopes are still in production, and the navigation systems applying these gyroscopes are still in operation. However, a strong trend is moving toward the development of quick connection type gyroscope to compete with the ring-shaped laser gyroscope. We have to emphasize that new solid-state inertia sensors including the ring-shaped laser gyroscope have a prosperous development potential.

#### 2.5.1 Ring-shaped laser gyroscope (RLG)

Beginning in mid-eighties, the ring-shaped laser gyroscope has been in the predominate position in application of new

inertia systems. For example, newer generation standard inertia instruments, based on the ring-shaped laser gyroscope, have been equipped in almost all main combat planes of the United States. All the U.S. Boeing Aircraft adopt the ring-shaped laser gyroscope inertia devices as their major navigation system. Main technical progresses of RLG are as follows:

- Precision has attained a high level of  $0.003^0/h$ ;
- Some new techniques against locking, such as zero locking and zero frequency deviation of speed have been developed; and
- Gyroscope upgrading leads to generalization and miniaturization of the system.

Generally, the ring-shaped laser gyroscopes will be the predominating gyroscope type in the inertia systems in the foreseeable future.

#### 2.5.2 Interference type fiber-optics gyroscope (IFOG)

According to the volume of development work and expenditure poured in, at present the most important new gyroscope is the fiber-optics gyroscope [1]. The basic model open-ring interference type fiber-optics gyroscope can only attain the level of low and intermediate precision ( $10^0/h$  to  $0.1^0/h$ ), mainly used as a zero velocity sensor for carriers (such as helicopters, branch route airliners, tactical missiles, and spacecraft) of low mobility flight or short-term operation.

In recent years, deviation stability of closed-ring interference type fiber-optics gyroscopes have attained a level between  $0.01^0/h$  to  $0.005^0/h$  in the range of limited environmental variations. Only such a fiber-optics gyroscope is adaptable to inertia systems. As reported, currently this type of gyroscope has been applied on quite a few occasions, such as the navigation attitude system of Boeing 777 airliners and Daniell 328 branch route passenger planes, the flight control system of remote

control anti-radar target planes, the navigation attitude system of NASA T-38 training planes, as well as the combination system of GPS and navigation attitude system (AHRS). As estimated, real inertia class fiber-optics gyroscopes will appear in the late nineties for navigation applications of cruise missiles and aircraft by the end of this century. There is such a prediction abroad: applications of fiber-optics gyroscopes in 1995 on intermediate and short range missiles will amount to 94 percent of total number of all gyroscopes while 4 percent for aircraft and 2 percent for warships or airships. By the year 2000, the application ratios will be 64, 20 and 16 percent, respectively [28].

#### 2.5.3 Hemisphere resonant gyroscope (HRG)

HRG is a new vibrating gyroscope. As indicated in test flights in 1990, it has good inertia performance with mean square root error at 2 n mile/h while data for the best gyroscope set is as high as 0.8 n mile/h.

Although HRG is closer to navigation level performance (as compared with fiber-optics gyroscope) in development, and systems suitable to tactical missiles are available, yet the comprehensive performance and cost of HRG are not a threat to the predominance of laser gyroscopes. From the most recent report, the Delco Corporation (the inventor and producer in the United States) recently announced cancellation of its wine glass gyro (the HRG) inertia system program [21]. The cancellation cast a dark shadow on its further development.

#### 2.5.4 Inertia sensor with micro-silicon structure

In techniques relating to inertia sensors, recently there has been an important trend, microelectronics is entering the field of inertia sensors [24]: a gyroscope and accelerator are

fabricated on a silicon chip. Their very tiny dimensions and the excellent electromechanical properties of silicon are very adaptable to heavy overloading. With their low cost, it is possible to introduce the inertia sensors and even inertia systems into various new military and commercial areas. Therefore, this is a new inertia sensor with good future. At present, there are sensors of this type entering the batch production stage.

(1) Accelerators with micro-silicon structure: this type is the one with the fastest development in micro-silicon sensors. At present, such new accelerators have been applied in newly developed quick connection systems.

(2) Digital type quartz gyroscope: technique of fabricating a tuning fork on a quartz chip is adopted. Batch production has begun for impending replacement on intelligent weapons, such as JDAM and JSOW. Ring-shaped laser gyroscopes have been adopted in inertia guidance systems [20].

### 3. Development Problems Appearing With Regularity

#### 3.1 The heaviest demand in military applications is in autonomous navigation.

In navigation positioning, locus of a moving object can be determined by measuring its position, velocity or acceleration. However, acceleration is the only physical quantity that can be measured inside the object. In inertia guidance, positioning calculation is conducted by measuring the acceleration of the moving object with double mathematical integration. Therefore, this is really an autonomous navigation system. In modern warfare, even higher requirements are necessary for survivability, stealthiness and mobility, thus requiring a navigation system to operate as silently as possible. Thus, the autonomy of inertia guidance systems provide valuable properties in military applications.

Since entering the nineties, inertia technique has faced the serious challenge of GPS. However, even the U.S. is not giving up inertia technique, as its military planners do not want to rely exclusively on the GPS system because an enemy may attack GPS satellites or jam GPS signals. Hence the Pentagon clearly pointed out in its navigation plan, "The positioning/navigation system of U.S. Defense will be based on GPS backed up by autonomous systems, such as inertia, doppler and terrain matching". [25]

When realizing autonomy in its broad sense, it is worrisome to users with respect to the systems like GPS being shared with international owners. We are unable to place the basic points of research and development of the GPS entirely under the jurisdiction of others. It is irreplaceable in the status of the inertia system as the central information source of aircraft.

3.2 Combined navigation provides the best performance-to-price ratio.

Since beginning of the eighties, with emergence of airborne computers of high computation speed and large memory capacity, achievements of modern control theory, and application of Karman filtration technique, research on combined navigation systems with multiple sensors has been scheduled [26]. The basic concept of this combined system is as follows: by using an inertia guidance instrument with intermediate precision to be combined with the Karman filter to form one or multiple supplementary sensors. In such a system, inertia guidance is the main navigation instrument. Functions of all supplementary sensors provide limited information for inertia guidance. The longer the time that the limited information is obtained, the more difficult is error estimation of the inertia system. These supplementary sensors are used to upgrade the basic inertia system, thus becoming the best combination system whatever for short and long term stability as well as system precision.

There are the following typical sensors for combination systems: GPS, doppler, Tacan, Roland, Omega, digital compass, digital map, radar altitude table, atmospheric data computer, and stellar tracker, among others. At present, defense departments of the nations of the world have the greatest interest in the combination of inertia/GPS. In addition to the fact that GPS has its absolute predominance in positioning precision with its precise timing function (GPS can provide four-dimensional navigation) that no other navigation devices possess, there is the very high complement between inertia guidance and GPS.

Future users mainly have requested upgrading of the five following aspects:

- Smaller dimensions, weight and power;
- Higher reliability;
- Lower initial purchasing cost and total service-life expenditures, expanding flexibility in tasks performed; and
- Improvements on system performance.

The combination of a quick connection inertia apparatus (this is the so-called intermediate precision standard inertia guidance instrument that Western nations usually adopt at present) of intermediate precision (positioning precision at 0.8 n mile/h (CEP), speed precision at 1 m/s (1 sigma)) and low cost with small air-borne GOS receiver, not only basically satisfies the above-mentioned requirements, but also can provide better performance-to-price ratio than any independent device. In the U.S., the GPS receiver in this combination system has been developed to the stage that its use in the GPS module in the inertia guidance box is feasible [3, 5] (such as models GEMI/II/III); however, currently in the United Kingdom and France, it is mostly still a simple GPS machine box [7]. Typical of such combination systems are H-764G, LN-93G, ULISS-G and LINS300-30/40. If a GPS module (or receiver) is dismantled, the

system can be used as a standard inertia guidance instrument.

The basic standard of attitude navigation direction of the dynamic tuning gyroscope has been developed into the dual-box AHRS/GPS combination system; typical of the system are LSR-85G, LN-93G and LINS300-30/40. In the most recent year, there are available such navigation attitude systems adopting the fiber-optics gyroscope; test flights are underway in order to combine with the inserted type GPS receiver; typical of these are LN-200G and LCR-93.

3.3 Intermediate precision satisfies the basic requirements of navigation for tactical planes.

As mentioned above, the intermediate precision inertia guidance instrument is the basis of a combination system for tactical fighter planes. This is due to the mission requirements. Among quite a few functions of the inertia guidance system of fighter planes, there are guidance of navigation route, firepower control and flight control data, sensor stability, and transfer alignment of aircraft weapon, among others. The first two functions are the most primary [25]. Since any type intermediate precision inertia guidance system can provide a navigation precision considerably exceeding that required by air-route navigation of fighter planes, the precision of inertia guidance systems of tactical planes is mainly determined by precision of messages required by firepower control. These messages include horizontal speed, vertical speed and pitch/roll. If GPS data are used in air route guidance to the index gyroscope and accelerometer, the speed precision at the instant of firing a weapon will be determined by transfer of persisting time and error of the inertia guidance system after final revision by GPS. This explains that GPS/INS combination will allow relaxing of precision requirements of the inertia system.

At the present time, all inertia guidance systems of tactical planes of the nations of the world have been developed according to intermediate precision standard inertia guidance instrument norm (ENAC77-1) of the U.S. Air Force. However, the newer generation ring-shaped laser gyroscope standard inertia guidance instruments follows a new norm of SNU84-1. At present, the main tactical fighter planes of the U.S., United Kingdom and France have equipped or are equipping the second generation laser gyroscope standard inertia guidance instruments.

3.4 Breaking the bottleneck of key techniques is a milestone on success of inertia sensors.

As is well known, the greatest amounts of research and development expenditures have been consistently laid out by the defense departments of the various nations. For each type of new gyroscope, 15 to 20 years are required from concept proposal to output of products. In the following, procedures of research and development are presented on several new types of gyroscope to explain the gigantic promotion of new processes, new materials and new techniques.

The concept of ring-shaped laser gyroscope was initiated in 1963. In 1973, a major breakthrough occurred in the laser gyroscope technique with performance upgraded by two orders of magnitude; in addition, problems of service lifespan were solved. However, batch production of laser gyroscopes came as late as 1983. As long as two decades elapsed for the entire cycle of research and development; the expenditure was more than 2 billion U.S. dollars. According to Pentagon regulations at that time, development expenditure can be allowed to exceed 2 billion U.S. dollars only when the project is determined to be an important weapon system. This means that the laser gyroscope is a key technique in the U.S. defense research. Once the key technique of a laser gyroscope has made a breakthrough, a leap forward is



realized for the inertia system from platform type to quick connection type.

The theory of the fiber-optics gyroscope was proposed in 1978. However, the low- and intermediate-precision fiber-optics gyroscopes gradually entered the production stage in late eighties. In the intervening time, successful development of anti-deviation optical fibers, superradiation light emitting diodes, and multifunction integrated optical chips are keys for upgrading performances of fiber-optics gyroscope and its practical applications.

The fundamental theory of the hemisphere resonant gyroscope was first advanced in 1890. However, as late as in 1978, the first prototype device (which attracted attention of fellow researchers) was built. In early nineties, a system using such a gyroscope appeared on the scene. From initiating of theory to output of products, almost a century elapsed for the hemisphere resonant gyroscope. This is mainly because the theory relating to such gyroscope can be realized in production only under the highly developed conditions at today's level of science, technology and industrial process.

As indicated by these examples, research and development of inertia sensors (in particular, the precision gyroscope instrument) is a very difficult and elaborate task. This is a high-tech product requiring vast investment and long development cycle.

3.5 Guided navigation technique is a dual-purpose technique for military and civilian applications

In the history of civilization, navigation technique was consistently closely related to production activities. Citing an example of aircraft navigation, instrumentation navigation occurred in the early twenties. Radio navigation occurred in the

thirties; and inertia navigation occurred in the fifties. Satellite navigation and combined navigation occurred in the nineties. In the development process of 70 to 80 years, navigation has been consistently used for the dual purpose of military and civilian applications.

However, inertia technique and military applications are more closely related. Hence, in the recent half century, the developed countries consistently considered the inertia navigation as a key technique. Even today, the inertia technique is still controlled by the U.S. government as a sensitive one. The GPS system is inherently a military system; however, this is a successful military and civilian dual-purpose program at the national level [17]. To seek the maximum commercial interests, the U.S. government encourages civilian applications of GPS; however, it is stressed to ensure satisfying requirements of national security. With the development of high technology today, the boundary between military and civilian technologies has been fuzzy as time goes on. The proportion of military and civilian dual-purpose techniques has been growing in the development of defense technology. Therefore, there is a common acknowledgement by all nations that the military and civilian dual-purpose attributes must be clearly understood with active encouragement of development and utilization. The wide range of GPS civilian applications is beyond the discussion contents of this chapter. Inertia guidance technique can serve civilian applications. For examples, under the water, in pristine forests, in tunnels, and in urban areas with densely placed buildings that GPS signals are unable to penetrate, the inertia technique is predominant in precise navigation, surveying and positioning. In addition, inertia technique applications in passenger cars may provide the biggest market in the near term.

Since entering the mid-nineties with the disintegration of the Soviet Union and conclusion of the Cold War, major

adjustments are underway of the development strategy of defense science and technology in various nations. The core of military strategy of many nations in the new era is to cope with regional threat and the preparation to win local high-tech wars.

Like other defense techniques, aircraft navigation is responsible, first of all, to carry out navigation and guidance for military flight vehicles by using the most recent contemporary technology. At the same time, there is the historical challenge of how to actively expand the application range in transition toward military and civilian dual-purpose techniques. For better developing China's aircraft navigation techniques, the author suggests to give sufficient emphasis to two following problems.

First, development of autonomous navigation is very important militarily. Although GPS technique is the contemporary navigation technique with the highest precision, yet we have to rely on our own capability to stress the development of combined navigation techniques based on inertia guidance.

Secondly, solid-state sensor and micro-electronics technology represent the major development direction of the field of navigation. Both will bring along good prospects of great strides in development of navigation technique in the 21st century. Hence we should in timely fashion develop the inertia devices of laser, optical fiber and microstructure, as well as the digital circuitry techniques, as important bases of the future combined guidance, in this way sufficiently utilizing the high-tech approach to promote the development of navigation technique in China.

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